

Study of banana dehydration using sequential infrared radiation heating and freeze-drying

Zhongli Pan^{a,b,*}, Connie Shih^b, Tara H. McHugh^a, Edward Hirschberg^c

^a *Processed Foods Research Unit, USDA-ARS-WRRC, 800 Buchanan Street, Albany, CA 94710, USA*

^b *Department of Biological and Agricultural Engineering, University of California, One Shields Avenue, Davis, CA 95616, USA*

^c *Innovative Foods Inc., 175 South Spruce Street, South San Francisco, CA 94080, USA*

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Abstract

The drying and quality characteristics of banana slices processed with a sequential infrared radiation and freeze-drying (SIRFD) method were investigated. Cavendish bananas slices with 5 mm thickness were predehydrated using IR heating at each one of three radiation intensities, 3000, 4000, and 5000 W/m² or hot air at 62.8 °C. The predehydrated samples with 20% and 40% weight reductions obtained using 4000 W/m² IR intensity were then further dried using freeze-drying for various times to determine the effect of predehydration on the drying rate during freeze-drying. To improve the quality of dried banana chips, the banana slices were also treated with a dipping solution containing 10 g/l ascorbic acid and 10 g/l citric acid before the IR predehydration. Control samples were produced using regular freeze-drying without the predehydration. The quality characteristics of dried banana chips, including color, thickness shrinkage and crispness, were evaluated. The predehydration results showed that the drying rate of IR heating was significantly higher than the hot air drying and increased with the increase of IR intensity. For example, it took 10 and 38 min to achieve 40% weight reduction by using IR at 4000 W/m² and hot air drying, respectively. However, the banana slices with IR predehydration dried slower during freeze-drying compared to the samples without predehydration, which was due to texture changes that occurred during the predehydration. Acid dipping improved product color and also reduced freeze-drying time compared to non-dipped samples. It has been concluded that SIRFD can be used for producing high crispy banana chips and additional acid dipping improved product color and reduced required freeze-drying time.

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1. Introduction

Banana is one of the important high sugar tropical fruit crops grown in many countries and is very susceptible to quality deterioration. Conventional hot air drying, which is the oldest method used in food preservation, has been widely applied for drying bananas. Due to the high sugar contents in bananas, drying them normally requires high temperatures and prolonged drying times, which can cause serious adverse changes in flavor, color, texture and nutrients of the finished products

(Maskan, 2000). The major disadvantages of hot air drying are low energy efficiency and lengthy drying times during the falling rate period. Because of the low thermal conductivity of food materials in the falling rate period, heat transfer to the inner sections of foods during conventional heating is limited (Feng & Tang, 1998).

Freeze-drying (FD) has been studied and used as a single process or in combination with other techniques to minimize the adverse quality changes associated with dried products (Hammami & Rene, 1997; Lin, Durance, & Scaman, 1998; Lin, Tsen, & King, 2005; Shishegarha, Makhlof, & Ratti, 2002). During freeze-drying, the freezing of the product stiffens its structure and subsequently prevents solute and liquid motion (Levine & Slade, 1989). The product from freeze-drying should be much crisper than the product from hot air

* Corresponding author. Processed Foods Research Unit, USDA-ARS-WRRC, 800 Buchanan Street, Albany, CA 94710, USA. Tel.: +1 510 559 5861; fax: +1 510 559 5851.

E-mail address: zpan@pw.usda.gov (Z. Pan).

drying. Despite its capability of providing a very high quality dehydrated product, freeze-drying is an expensive method which limits its wide utilization by the food industry. Thus, the use of freeze-drying by the food industry is normally restricted to high value products, such as coffee, crispy fruits and vegetables, ingredients for ready-to-eat foods and some aromatic herbs.

Infrared (IR) heating offers many advantages over conventional hot air drying. When IR is used to heat or to dry fruits, the radiation impinges on the exposed fruit surfaces and penetrates to create internal heating with molecular vibration of the material, and the energy of radiation is converted into heat (Ginzburg, 1969). The depth of penetration depends on the composition and structure of the fruits and also on the wavelengths of IR radiation. When the food is exposed to IR radiation, the electromagnetic wave energy is absorbed directly by the dried food with low energy loss. It has been reported that the drying rate for food materials using IR heating is higher compared to conventional hot air drying and increases with increased power supply to a far infrared emitter (Masamura et al., 1988). The IR heating allows more uniform heating of fruits resulting in better quality characteristics than other drying methods (Nowak & Lewicki, 2004; Sakai & Hanzawa, 1994).

Combination of IR radiation with convection heating and/or vacuum has also been studied (Abe & Afzal, 1997; Hebbar, Vishwanathan, & Ramesh, 2004; Kumar, Hebbar, Sukumar, & Ramesh, 2005; Mongpraneet, Abe, & Tsurusaki, 2002). The combined infrared radiation and hot air heating is considered to be more efficient over radiation or hot air heating alone as it provides a synergistic effect. Afzal, Abe, and Hikida (1999) reported that the use of combined far infrared radiation and hot air drying resulted in faster drying and considerably less energy consumption than using hot air drying alone. A combination of IR and freeze-drying was also studied for drying sweet potato (Lin, Tsen, & King, 2005).

Since it offers higher drying rate and better color retention in the products than other drying methods (Nowak & Lewicki, 2004; Sakai & Hanzawa, 1994), IR drying may be used as a predehydration method before freeze-drying. A sequential infrared radiation and freeze-drying (SIRFD) method has been investigated in this research as a means for producing high quality, crispy, dried banana chips with an aim at reducing drying time leading to reduce energy consumption. The SIRFD method is a two-step drying process of infrared predehydration followed by freeze-drying. In our other drying study, it has shown that using the SIRFD could effectively reduce the freeze-drying time and overall drying time, as well as improve the crispness of strawberry slices (Shih, Pan, McHugh, Wood, & Hirschberg, 2008).

Dipping treatment is one of the effective methods that can be used to minimize the enzymatic browning in fruits and vegetables. Chemical compounds, such as ascorbic acid and citric acid, have been well studied and used in the food industry (Demirel & Turhan, 2003; Doymaz, 2004). Ascorbic acid is an antioxidant that keeps fruit from darkening during drying. Citric acid also acts as antidarkening agent (Zhu, Pan, &

McHugh, 2007). It is reasonable to consider using such dipping treatment before IR predehydration to improve the color of dried bananas.

The objectives of this study were to investigate the drying characteristics of banana slices using the SIRFD method and evaluate the effects of IR predehydration and dipping treatment on the quality of freeze-dried crispy banana chips.

2. Materials and methods

2.1. Materials

Cavendish bananas at color stage #6 were obtained from a local supermarket. Prior to drying, the bananas were first peeled and cut into 5 mm thick slices. Some sliced samples were dipped in a solution containing 10 g/l ascorbic acid and 10 g/l citric acid for 1 min before any drying treatment, which was adopted based on a practice used in the food industry. The banana slices were dried using various methods including IR, hot air, and freeze-drying. Banana initial moisture content was 73.0 g moisture/100 g wet weight.

2.2. Moisture content determination

To determine the moisture content of the fresh and dried banana samples, banana samples of 10–15 g were placed in pre-weighed aluminum weighing dishes and dried according to AOAC Official Methods of Analysis (1995) (70 °C for 48 h at 29 Hg vacuum) in a vacuum oven (Model No. V01218A, Lindberg/Blue, Asheville, NC). The dishes were removed and weighted after 48 h drying. The balance used for the measurement had an accuracy of 0.01 g (Model No. 602, Denver Instrument Co., Arvada, CO). Three samples from each trial were used for the moisture determination and the average moisture content is reported.

2.3. Experimental design and drying procedures

To compare the drying characteristics of IR and hot air drying, banana slices were dried at three IR intensities, 3000, 4000, and 5000 W/m² and hot air at 62.8 °C. The weight changes were measured every minute using a digital balance during the drying. The 3000 W/m² IR intensity had lowest drying rate among the tested intensities. The 5000 W/m² IR intensity had the highest drying rate, but it caused discoloration of finished products at high weight reduction levels. Therefore, only 4000 W/m² was then selected for producing predehydrated samples for freeze-drying. Both dipped and undipped samples were dried using IR to remove 20% and 40% of the initial weight. The weight reduction levels were determined for reasonably maintaining the texture integrity without causing too much shrinkage after IR drying. The predehydrated samples and a control sample without predehydration were further dried using freeze-drying to a final moisture content of about 5 g moisture/100 g wet weight for quality evaluation. The evaluated quality parameters included color, thickness shrinkage and crispness. All drying experiments

were conducted in triplicate and the data reported in Section 3 are average values.

2.4. IR and hot air predehydration

A catalytic infrared (CIR) dryer/dehydrator equipped with two catalytic IR emitters powered with natural gas (Catalytic Infrared Drying Technologies LLC, KS) was used in this study. The CIR dryer consisted of infrared emitters of area 30×60 cm with a wave guard around the IR emitters to prevent infrared radiation from escaping and to keep heating uniform. With the wave guard, the heating area was 34×64.5 cm. The drying tray was placed in between the two IR emitters in parallel position of the emitter face. Banana slices were heated from both the top and bottom sides. An automatic data acquisition and control system developed in our laboratory was used to control and record various operation parameters. The schematic diagram of the equipment is shown in Fig. 1. The IR dryer was operated with a continuous heating mode. For the continuous heating, the natural gas was continuously supplied to the emitters. The continuous heating could take advantage of delivering high heat to the product in a relatively short time for quick drying. The change in sample weight during the drying process was measured using a digital balance until at least 40% weight reduction was reached.

Banana slices were arranged in a single layer on the drying tray (metal screen) which was sprayed with PAM cooking spray to prevent bananas from sticking to the tray. The banana slices were placed within the confines of the wave guard at a loading rate of approximately 2.1 kg/m^2 . After infrared predehydration, the banana slices were transferred to wax paper by flipping the drying tray and then transported to a large scale air blast freezing system with temperature of -18°C .

For comparison, a hot air dryer of Proctor & Schwartz Cabinet Dryer (Product code 062, Proctor & Schwartz, Inc., Horscham, PA) was also used to dry the banana samples to obtain the drying curve. The hot air dryer was set at 62.8°C and the sample weight changes were also measured using a digital balance during drying.

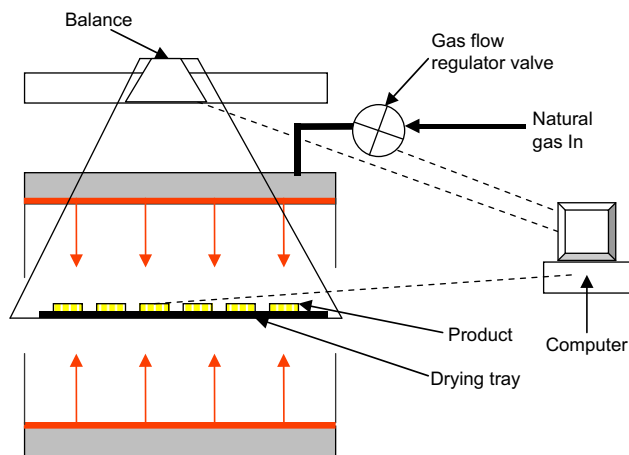


Fig. 1. Schematic diagram of the catalytic infrared dryer.

2.5. Freeze-drying

The dipped and undipped frozen samples with 20% and 40% weight reductions achieved with IR heating and the control samples were removed from the freezer after they were completely frozen and then placed in a pilot scale freeze dryer (VirTis Ultra/VirTual Series EL unit). The freeze dryer was operated in shelf driven mode, which was controlled based on shelf temperature, and run with programmed procedures.

In order to determine the drying characteristics of the banana slices during freeze-drying, the samples were dried for various times of up to 40 h. The samples were weighed at the end of each time period and the moisture content was calculated and reported. The samples with moisture content higher than 5 g moisture/100 g wet weight were further dried to obtain a similar moisture content for all samples used for quality evaluation.

2.6. Quality evaluation

2.6.1. Color

L.a.b. color measurements of banana sliced before and after drying were performed using a Minolta CR-200 reflectance colorimeter (Minolta, Japan). To obtain representative color of the samples, the dried banana samples were ground to powder using a small-scale blender to obtain all particles that passed a 100 mesh screen. A sample of 1 g of banana powder was put in a 5 cm diameter plastic Petri dish. The lens of the colorimeter covered with a plastic wrap was directly placed on banana powder to measure the color values. Three measurements for each sample were performed and average value is reported.

2.6.2. Thickness shrinkage

The thicknesses of the fresh and dried samples were measured using a Cen-tech electronic digital caliper (Harbor Freight Tools, Camarillo, CA). The percentage shrinkage was determined based on the initial and final thickness. Ten pieces of banana samples from each drying treatment were measured and the average thickness shrinkage is reported.

2.6.3. Crispness

Crispness is attributed to intermolecular bonding of starch forming small crystalline-like regions when little water was present. These regions require force to break apart, which gives the food a crispy texture. The detailed definitions and calculation methods of crispness were adopted from [Texture Technologies \(1998\)](#). Crispness was evaluated using a TA.XT2 Texture Analyzer (Texture Technologies Corp., North America). Dried banana samples were tested using a $\frac{1}{4}$ " diameter ball probe and an accompanying chip/cracker fixture (TA-101). A "pipe" cylinder with an outside diameter of 25 mm and an inside diameter of 18 mm was mounted on the plate component of the TA-101 to support a banana piece for the test. The measurement settings on the Texture Analyzer were pre-test speed of 3.0 mm/s and test speed of 5.0 mm/s. The values of initial slope, indicating crispness, were

measured and calculated. Five replicates for each treatment were performed.

2.7. Scanning electronic microscopy (SEM)

In order to evaluate the structural changes of banana slices by the different drying methods and better understand the mechanism of water transport during drying, electron microscopy studies of the cross section of dried banana samples were performed. Selected dried banana samples were carefully cut using sharp razor blades (Feather, Ted Pella, Inc., Redding, CA) to expose a fresh cut surface of the cross section. Specimens were mounted onto aluminum stubs using double-coated carbon tabs (Ted Pella, Inc., Redding, CA), sputter-coated with gold-palladium using a Denton Desk II sputter coating unit (Denton Vacuum, Moorestown, NJ) and photographed in a Hitachi S-4700 field emission scanning electron microscope (Hitachi, Japan) at 2 kV. Digital images were captured at 1280×960 pixel resolution with $40\times$ of magnification.

2.8. Statistical analysis

Analysis of variance (ANOVA) and the test of mean comparison according to Tukey's honest significant difference (HSD) were conducted with the level of significance of 0.05. The statistical software, SAS System for windows, version 9.0 (SAS institute, Cary, NC), was used for the analysis. The parameters of nonlinear model were calculated using SigmaPlot (Scientific Graphing Software, version 3, Jandel Corporation).

3. Results and discussion

3.1. Heating and drying rates of IR and hot air drying

The heating rate of banana slices was closely related to the IR heating intensity. The high radiation intensity allowed for faster temperature increase in product (Fig. 2). With radiation intensity of 5000 W/m^2 , the center temperature of product

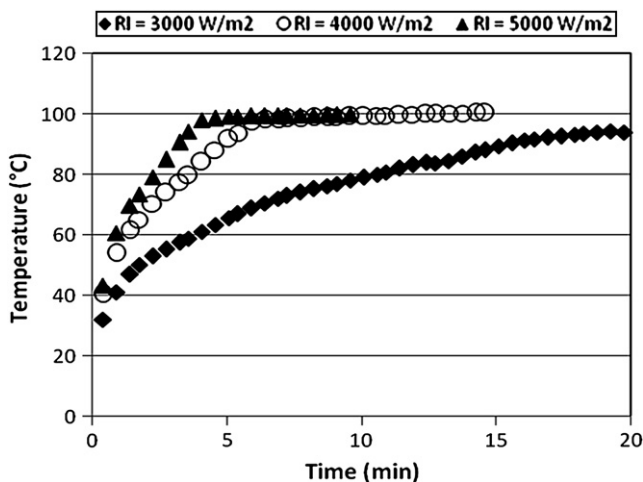


Fig. 2. Temperature of banana under different radiation intensities (RI – radiation intensity).

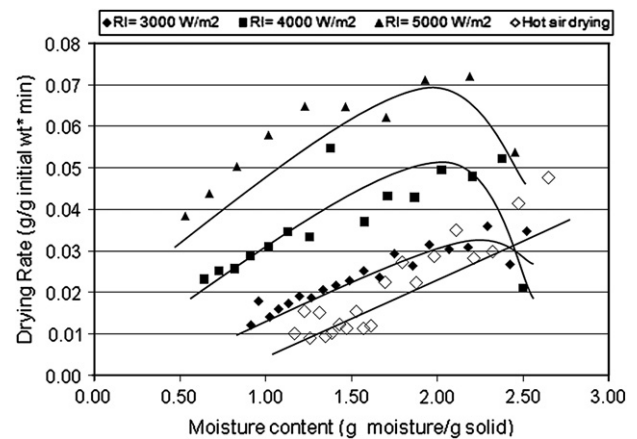


Fig. 3. Drying rates of different drying methods and conditions of banana slices.

reached a temperature of close to 100°C after 3 min of heating compared to about 5 min for 4000 W/m^2 . But the heating rate less than 3000 W/m^2 was very low. If fast heating is desired, it is essential to use high IR intensity.

The IR drying tests showed much higher drying rates throughout the course of drying than the hot air drying (Fig. 3). Since infrared radiation directly penetrated into the banana and did not heat the surrounding air as that in the hot air drying, infrared drying rate was much higher than the hot air drying. Therefore, the drying rate of the infrared radiation was much higher than that obtained from the hot air drying.

The drying rates varied with the radiation intensity as expected. In infrared drying tests, there was an absence of or very brief appearance of a constant rate period. This could be because of the quick drying on the surface of products at high temperature. The hot air drying tests showed more of a distinct immediate entrance into the falling rate period.

The sample weight reduction results also showed that the IR drying was much faster than that in hot air drying (Fig. 4). For example, the IR heating took 3.1 and 6.2 min

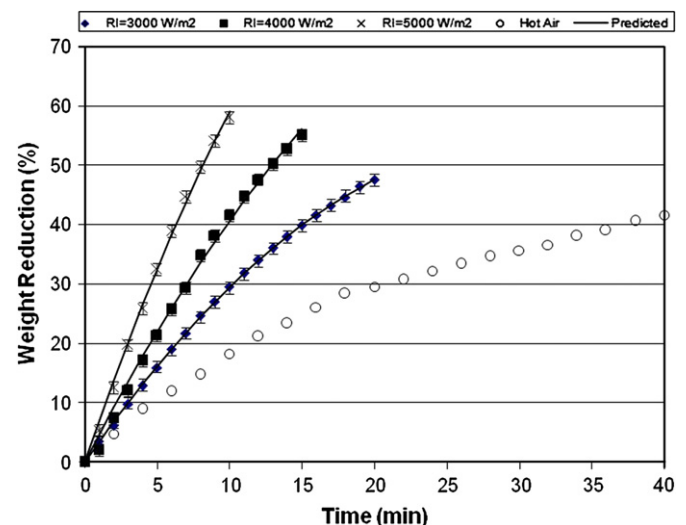


Fig. 4. Weight reduction of banana samples with IR and hot air drying.

to obtain a 20% and 40% weight reduction with 5000 W/m² radiation intensity as compared to 11.2 and 37.3 min for hot air drying, respectively. This was a 72.3% and 83.4% time reduction or improvement of processing efficiency for the 20% and 40% weight reduction, respectively.

The rate of weight reduction increased with the increase in radiation intensity. It took 15.9, 9.5 and 6.2 min to achieve 40% weight reduction with the radiation intensities of 3000, 4000, and 5000 W/m², respectively. This could be because more heat was absorbed by the banana slices at a higher IR intensity.

Nonlinear regression equations were developed for predicting the weight reduction with the three radiation intensities at a given time (Eqs. (1)–(3) for radiation intensity at 3000, 4000, and 5000 W/m², respectively).

$$WR = -0.0559t^2 + 3.4956t \quad (1)$$

$$WR = -0.0641t^2 + 4.698t \quad (2)$$

$$WR = -0.1153t^2 + 7.0529t \quad (3)$$

where WR is the weight reduction (%) and t is the time (min). The predicted weight reduction fits well ($R^2 = 0.99$) with the experimental weight reduction (Fig. 4). Therefore, the empirical regression equations can be used to predict the weight reduction under known drying process conditions.

3.2. Freeze-drying characteristics

For preparing the freeze-drying sample, radiation intensity of 4000 W/m² was selected to pre-dry the banana slices due to better control of desired weight reduction and better appearance in the pre-dried banana slices. The results of freeze-drying process showed that infrared radiation predehydration of banana slices did not reduce the required freeze-drying times to reach a specific moisture content as compared to the regular freeze-drying without predehydration (Fig. 5). The samples

with 20% and 40% weight reductions and no dipping treatment took 23 and 38 h to achieve the final moisture content of 5 g moisture/100 g wet weight compared to 21.1 h for the non-predehydrated (regular FD) sample. The results were opposite from what has been observed with strawberry slices in our other studies (Shih et al., 2008). This could be due to shrinkage or crust formation during the predehydration of banana samples, which was confirmed by the micrographs of the dried banana from SEM.

The regular freeze-dried banana (Fig. 6a) had uniform and small porous structure, but no damage and disruption of cellular walls at the heated surface. On the other hand, the IR pre-treated samples with 20% WR (Fig. 6b) and 40% WR (Fig. 6c) showed collapse of cellular tissue in the surfaces of the banana slices, forming a crust on the surfaces of the banana slices. This is as expected since the surfaces were exposed to heat during drying. Crust formation is more apparent in higher weight reduction. The formation of crust resulted in reduced drying rate during freeze-drying. It was also observed that large pores existed in the center region of the banana slices with 20% weight reduction, which could be due to water vapor created during IR drying. The water vapor forced the expansion of the cellular tissue and pores. However, when the banana slices were further dried to 40% weight reduction, the pores were collapsed. The crust formation and changes in the pore sizes could affect the quality characteristics of the dried banana chips.

It was observed that the acid dipping treatment prior to IR drying improved the drying rate during freeze-drying compared to the samples without the dipping treatment (Fig. 5). The reason could be because the acid treatment washed out some starch, sugar and protein from the surface of banana slices, resulting in formation of more porous surfaces. However, the effect of improving drying rate was mainly observed during the early drying stage. The dipped samples with 20% weight reduction in IR predehydration required 2 h less than regular freeze-drying to achieve 5 g moisture/100 g wet weight in the finished products. But, the drying rate of the samples with 40% weight reduction in predehydration was much lower than regular freeze-drying even with the dipping treatment. More studies need to be done to further characterize and explain the effect of the acid treatment on the drying rate.

3.3. Color

Table 1 shows the results of color measurements of fresh and dried banana samples. The L color parameter indicates whiteness of the product. The b color parameter measures the yellowness of the product. The a parameter is reported as a reference even though it is not closely related to the color quality of dried bananas. Preferred colors are light or light golden color. In general, the drying treatment resulted in significantly improved whiteness (increased L value). But the yellowness of IR dried samples was stronger than the fresh and regular freeze-dried samples resulting in a golden color tone of dried products.

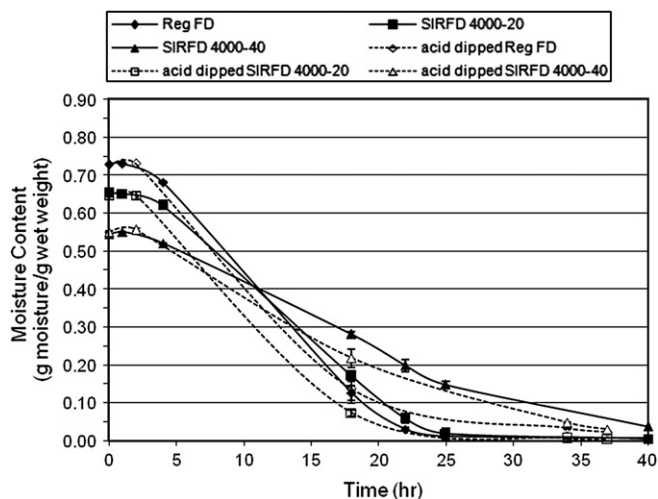


Fig. 5. Freeze-drying curves of all drying methods and treatments for banana slices.

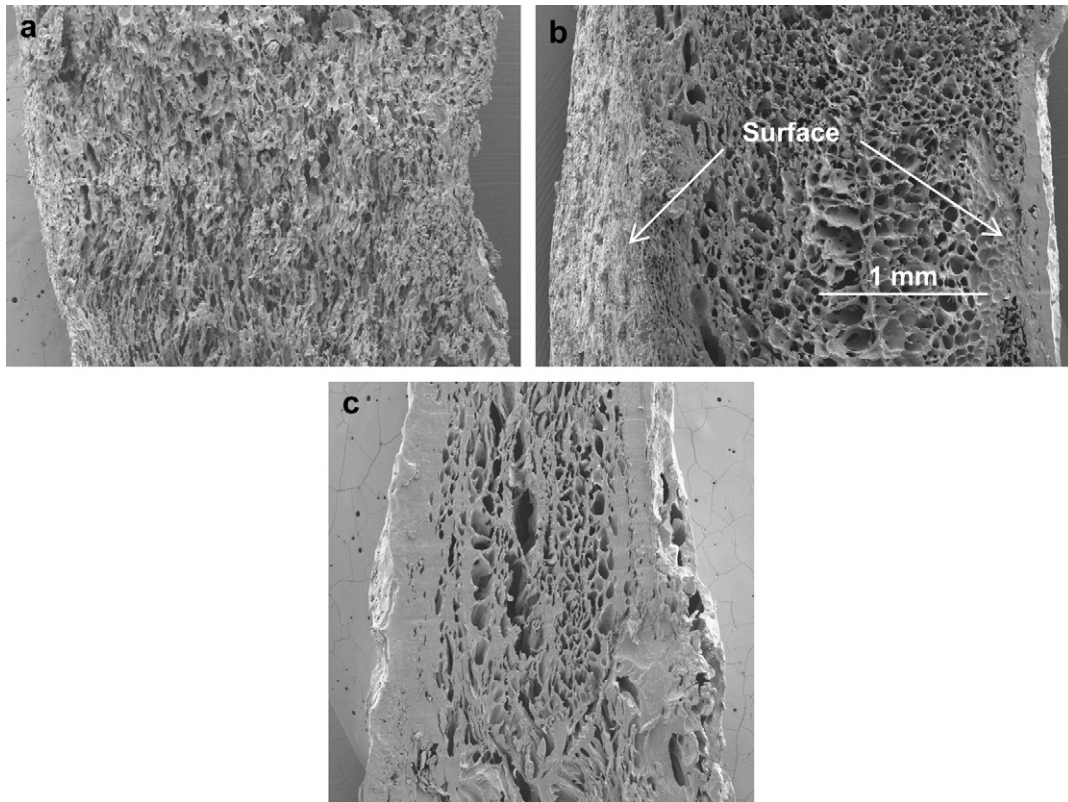


Fig. 6. SEM of cross section of dried banana slices with no acid treatment under different drying methods. (a) Regular FD, (b) IR predehydration, 20% weight reduction, (c) IR predehydration, 40% weight reduction.

When the weight reduction in predehydration increased, the L values decreased and values of a and b increased, which could be due to extended IR drying time causing browning. The results indicated that the yellow color developed at high weight reduction level with IR heating. When the acid dipping treatment was used, the samples had much whiter appearance compared to the undipped samples. Such color appearances can also be seen in Fig. 7. Likewise, the regular FD sample has less yellowness than the SIRFD samples. The results of reduced discoloration in acid dipped slices were similar to that observed in the study of air drying of Dwarf Cavendish and Gros Michel banana slices by Demirel and Turhan (2003).

3.4. Thickness shrinkage

Banana thickness shrinkage was evident in all drying methods and conditions used in this study (Fig. 8). Statistical

analysis results indicated that drying method ($p < 0.05$) had a significant effect on the thickness shrinkage of the final product. Since regular FD sample was not predehydrated, structural rigidity was created during the freezing stage of the drying process. This rigidity prevented collapse of the solid matrix after drying (Mujumdar, 1995). The thickness shrinkages were 5.9% and 11.5% for the regular FD samples with and without acid dip, respectively. Compared to regular FD samples, SIRFD samples experienced more thickness shrinkage for both the undipped and dipped samples. Furthermore, more shrinkage was observed with 40% weight reduction in predehydration than the 20% weight reduction. For example, for the undipped banana slices, 40% weight reduction samples had 33.6% thickness shrinkage as compared to 23.1% for the 20% weight reduction. This is due to the fact that more moisture was removed from the sample during the predehydration stage and also longer drying time required to obtain 40%

Table 1
Measured color results of fresh and dried banana slices

		Drying methods					
		Without acids dip				With acid dip	
		Regular FD	4000 W/m ² SIRFD		Regular FD	4000 W/m ² SIRFD	
			20% WR	40% WR		20% WR	40% WR
L	65.13 ± 0.70	92.54 ± 0.08	84.48 ± 0.03	80.88 ± 0.03	93.92 ± 0.01	87.79 ± 0.04	85.52 ± 0.03
a	−1.86 ± 0.09	−1.36 ± 0.01	−1.22 ± 0.01	−0.14 ± 0.02	−1.08 ± 0.02	−0.97 ± 0.02	−0.41 ± 0.02
b	16.43 ± 0.02	14.44 ± 0.08	17.54 ± 0.01	19.18 ± 0.04	12.92 ± 0.02	17.40 ± 0.11	18.86 ± 0.06

Note: FD — freeze-drying; WR — weight reduction; SIRFD — sequential infrared and freeze-drying.

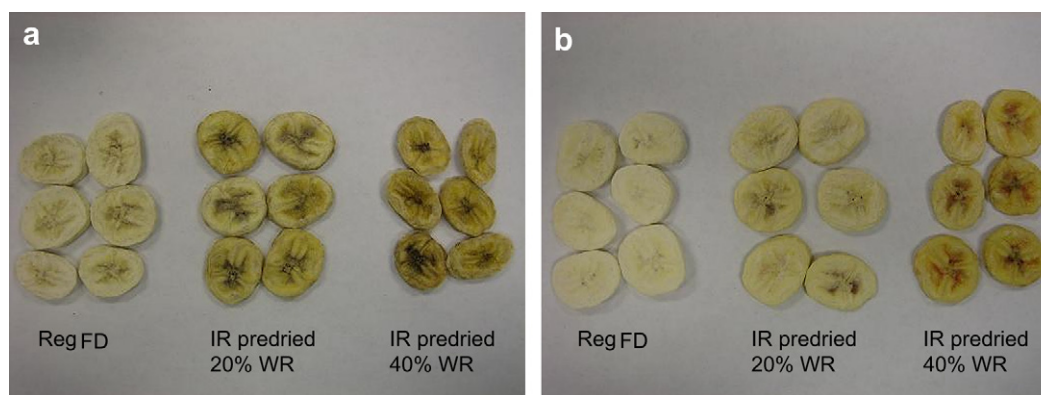


Fig. 7. Effect of acid dipping treatment on appearance of dried bananas. (a) Untreated bananas samples, (b) acid treated banana samples.

weight reduction than 20% weight reduction. Ketelaars, Jomaa, Puigalli, and Coumans (1992) found the shrinkage during drying is attributed to moisture removal and stresses developed during drying.

The shrinkage results also showed that the shrinkage was affected by the ascorbic and citric acid dip. Statistical analysis results indicated that acid dip ($p < 0.05$) had a significant effect on the shrinkage of the final product. There was a dramatic decrease in thickness shrinkage for acid dipped slices compared to undipped samples. For example, the thickness shrinkage decreased from 23.1% of undipped sample to 8.3% of dipped samples with 20% weight reduction. The extent of the change in the thickness of banana slices by the dipping treatment exhibited a considerable variation in literatures. Demirel and Turhan (2003) found that Cavendish slices shrank 47% during air drying but dipping did not affect the shrinkage during drying.

3.5. Crispness of banana slices

The crispness of banana slices treated with or without dipping after regular freeze-drying or SIRFD process is shown in Table 2. The sample processed with SIRFD had much higher crispness than the samples processed with regular freeze-drying. The crispness also decreased as weight reduction increased.

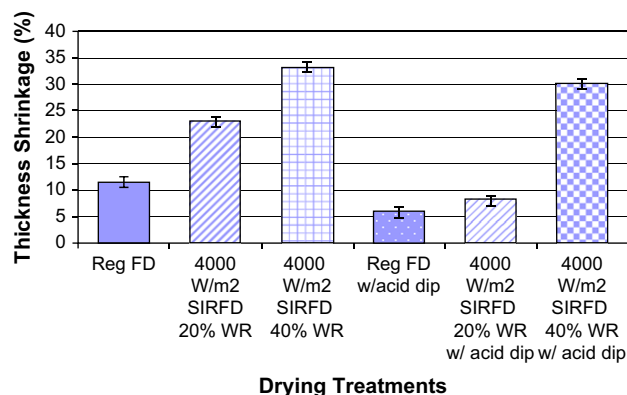


Fig. 8. Thickness shrinkage of dehydrated banana slices under different treatments.

The crispness was mainly related to the crust formation and structural change. The 20% weight reduction in predehydration formed modest crust and created large porous structure in the central region, resulting in high crispy product. However, the pores in the central region collapsed and thick crust formed at high weight reduction level due to IR heating, which was corresponded to reduced crispness. The similar trend was also seen in the acid dipped samples. However, the acid dipped samples had lower crispness than the undipped samples. Statistical analysis results indicated that drying method ($p < 0.05$) and acid dip ($p < 0.05$) had a significant effect on the crispness of the final product.

4. Conclusions

The IR drying had much higher drying rate compared to the hot air drying. Its drying rate increased remarkably with the increase of the radiation intensity. The banana chips dried with SIRFD had much crisper texture and golden color appearance than the regular freeze-dried products. The IR predehydration did not reduce the required drying time during the subsequent freeze-drying process. It also resulted in more shrinkage of finished product compared to regular freeze-dried products. However, the acid dipping treatment was an effective treatment method for improving the color appearance and reducing the freeze-drying time and the shrinkage. Even though the drawback of acid dipping was reduced crispness of finished products compared to undipped products, the products produced with SIRFD plus acid dipping still had similar or

Table 2
Crispness characteristics of banana slices dried with different treatments

Drying treatments	Crispness (g/mm)
Reg FD	1227.5 ± 155.1 ^{bc}
4000 W/m ² SIRFD 20% WR	2514.4 ± 571.0 ^a
4000 W/m ² SIRFD 40% WR	1887.1 ± 139.3 ^{ab}
Reg FD w/acid dip	1067.9 ± 148.9 ^c
4000 W/m ² SIRFD 20% WR w/acid dip	1802.5 ± 339.5 ^b
4000 W/m ² SIRFD 40% WR w/acid dip	1513.0 ± 466.9 ^{bc}

Note: FD — freeze-drying; WR — weight reduction; SIRFD — sequential infrared and freeze-drying.

Values followed by different letters are significantly different at $p < 0.05$.

higher crispness with much whiter color compared to regular freeze-drying. Therefore, food industry may use SIRFD alone to produce high crispy product or add dipping treatment to improve the product color.

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References

- Abe, T., & Afzal, T. M. (1997). Thin-layer infrared radiation drying of rough rice. *Journal of Agricultural Engineering Research*, 67, 289–297.
- Afzal, T. M., Abe, T., & Hikida, Y. (1999). Energy and quality aspects during combined FIR-convection drying of barley. *Journal of Food Engineering*, 42, 177–182.
- Demirel, D., & Turhan, M. (2003). Air-drying behavior of Dwarf Cavendish and Gros Michel banana slices. *Journal of Food Engineering*, 59, 1–11.
- Doymaz, I. (2004). Convective air drying characteristics of thin-layer carrots. *Journal of Food Engineering*, 61(3), 359–364.
- Feng, H., & Tang, J. (1998). Microwave finish drying of diced apples in a spouted bed. *Journal of Food Science*, 63, 679–683.
- Ginzburg, A. S. (1969). Application of Infra-red Radiation in Food Processing. Leonard Hill.
- Hammami, C., & Rene, F. (1997). Determination of freeze-drying process variables for strawberries. *Journal of Food Engineering*, 32, 133–154.
- Hebbbar, H. U., Vishwanathan, K. H., & Ramesh, M. N. (2004). Development of combined infrared and hot air dryer for vegetables. *Journal of Food Engineering*, 65, 557–563.
- Ketelaars, A., Jomaa, W., Puigalli, J., & Coumans, W. (1992). Drying shrinkage and stress. In A. S. Mujumdar (Ed.), *Drying'92, Part A* (pp. 293–303). Amsterdam, The Netherlands: Elsevier.
- Kumar, D. G. P., Hebbbar, H. U., Sukumar, D., & Ramesh, M. N. (2005). Infra-red and hot-air drying of onions. *Journal of Food Processing and Preservation*, 29, 132–150.
- Levine, H., & Slade, L. (1989). A food polymer science approach to the practice of cryostabilization technology. *Comments Agricultural Food Chemistry*, 1, 315–396.
- Lin, T., Durance, T., & Scaman, C. (1998). Characterization of vacuum microwave, air and freeze dried carrot slices. *Food Research International*, 31(2), 111–117.
- Lin, Y., Tsen, J., & King, V. (2005). Effects of far-infrared radiation on the freeze-drying of sweet potato. *Journal of Food Engineering*, 68, 249–255.
- Masamura, A., Sado, H., Honda, T., Shimizu, M., Nabethani, H., & Hakajima, M., et al. (1988). Drying of potato by far infrared radiation. *Nippon Shokuhin Kogyo Gakkaishi*, 35, 309–314.
- Maskan, M. (2000). Microwave/air and microwave finish drying of banana. *Journal of Food Engineering*, 44, 71–78.
- Mongpraneet, S., Abe, T., & Tsurusaki, T. (2002). Accelerated drying of welsh onion by far infrared radiation under vacuum conditions. *Journal of Food Engineering*, 55, 147–156.
- Mujumdar, A. S. (1995). *Handbook of industrial drying* (2nd ed.). New York: Marcel Dekker, Inc.
- Nowak, D., & Lewicki, P. P. (2004). Infrared drying of apple slices. *Innovative Food Science and Emerging Technologies*, 5, 353–360.
- Sakai, N., & Hanzawa, T. (1994). Applications and advances in far-infrared heating in Japan. *Trends in Food Science & Technology*, 5(11), 357–362.
- Shih, C., Pan, Z., McHugh, T. H., Wood, D., & Hirschberg, E. (2008). Sequential infrared radiation and freeze-drying method for producing crispy strawberries. *Transactions of the ASABE*, 51(1), 205–216.
- Shishegarha, F., Makhlouf, J., & Ratti, C. (2002). Freeze-drying characteristics of strawberries. *Drying Technology*, 20(1), 131–145.
- Texture Technologies. (1998). Quantify brittleness and crispness. Available from: www.texturetechnologies.com. Accessed 22.07.05.
- Zhu, Y., Pan, Z., & McHugh, T. H. (2007). Effect of dipping treatments on color stabilization and texture of apple cubes. *Journal of Food Processing and Preservation*, 31, 632–648.